

## CURRENT GAS TURBINE DEVELOPMENTS AND FUTURE PROJECTS

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### ABSTRACT

On behalf of its members, the Electric Power Research Institute (EPRI) conducts research on combustion turbines with the goal of bringing down generation costs and mitigating risk. Through its durability surveillance program, EPRI works closely with power producers and vendors to document performance, reliability, and maintenance costs for these new machines. EPRI is also striving to advance combustion turbine technology by developing new designs and promoting programs to extend the boundaries of CT performance. Development of the Cascaded Humidified Advanced Turbine (CHAT) and Intercooled Aeroderivative (ICAD) are the result of EPRI's commitment to cost-effective, efficient technologies. Looking beyond present cycle performance, EPRI is investigating ways to combine successful technologies to create new cycles with efficiencies approaching 65%. Through collaborative research with its funders, DOE, and national labs, EPRI is committed to improving the competitive position of its member power producers.

### INTRODUCTION

The Electric Power Research Institute (EPRI) conducts extensive combustion turbine research on behalf of its member power producers—which now include independent power producers (IPPs), other non-utility generators (NUGs), and international power producers, in addition to domestic utilities and their affiliates. With some 700 members, EPRI represents approximately 70% of all electricity generated in the United States.

In response to power industry restructuring, EPRI is focusing on technologies that provide immediate competitive benefits to its members while maintaining a core program of long-term strategic R&D. Combustion turbines—central to the success of power producers in the restructured marketplace—are a high priority.

As competition drives down electricity prices, power producers face a purchase dilemma: The efficiency edge promised by advanced CTs becomes ever more crucial,

but new, unproven models pose an investment risk. To mitigate this risk, EPRI monitors new commercial releases to pinpoint and resolve operational problems. We also convey utility needs to vendors, facilitating continued advances in the efficiency and reliability of next-generation designs. Further, we develop our own innovative cycles with higher efficiency, lower capital cost, and improved cycling flexibility.

Another important part of EPRI's program is to keep the industry abreast of recent turbine developments. In addition to publishing updates for our members, we have cosponsored topical turbine workshops with DOE, the Gas Research Institute, and utility hosts.[1] These workshops, which bring together power producers, equipment manufacturers, gas suppliers, government, and research organizations have included "Small Gas Turbines for Distributed Generation[2]," "Repowering with Current and Advanced Turbines," "Flexible, Midsize Gas Turbine Program Running Workshop," and an annual workshop on gasification and advanced turbines. Through these activities, EPRI helps power generators cost-effectively operate the best design for the job.

This paper focuses on the growing market dominance of increasingly efficient and reliable simple- and combined-cycle plants; the EPRI program for durability surveillance of these new products; and the development of advanced cycles and their prospects for ultimate efficiency growth.

### NEW COMBUSTION TURBINES AND COMBINED-CYCLE PLANTS

The number of new, commercially available combustion turbine and combined-cycle plants has burgeoned in the last decade. This section focuses on plants that employ "traditional" simple- and combined-cycles, which fall into two general classes: "heavy-frame" machines designed specifically for ground power, and "aeroderivative" engines adapted from civil or military air transport.

Traditionally, heavy-frame machines were distinguished from aeroderivative engines by their low first cost and high reliability. They operated at relatively low turbine rotating inlet temperatures (TRIT), employed lower technology alloys, and used no—or less sophisticated—blade cooling. However, these distinctions have become blurred as declining military spending, low gas prices, and deregulation of the electric industry have driven explosive changes in the heavy frames. In addition, features such as single crystal blading, aircraft compressor design techniques, high technology blade cooling, and thermal barrier coatings have become common features of heavy-frame machines such as the GE 7/9 series, the Siemens V84.3A, and the Westinghouse 501F/701F. As a result of their single-shaft design, heavy-frame machines have a relatively limited variable compressor geometry. In turn, their pressure ratios are lower than those of aeroderivatives, and they emit less nitrogen oxide (NO<sub>x</sub>) emissions.

The developments outlined above have greatly increased efficiency and lowered capital cost per kilowatt. However, the development pace decelerated as the most readily available technical advances were exploited, and the intractable competition for air for NO<sub>x</sub> control and blade cooling has reached an impasse. Figure 1 illustrates the historical trends in heavy-frame combined-cycle efficiencies.

The industry is now at a crossroads, searching for new advances. As is often the case in technology progress, the “new” path heads re-examining more complex cycles previously neglected because of perceived drawbacks such as cost, control, reliability, and availability. With dizzying suddenness, new machines that incorporate re-heat, steam cooling, recuperation, and humidification cycles have reached the market. The ABB GT24/GT26 series has

pioneered sequential combustion (reheat), with the first machine approaching commercial acceptance at GPU GENCO’s Gilbert Station. The Westinghouse 501G/701G machines and the GE 7H/9H, which employ steam cooling for the turbine blades, are on test. Cascaded humidified advanced turbines (CHAT) incorporating intercooling, reheat, recuperation, and humidification are available for order in both small (10–25 MW) and large (300 MW) sizes. Finally, aeroderivative turbines with intercooling have been studied and are near commercial development in small (10–15 MW) and large (60–150 MW) sizes. Figure 2 maps the range of machines by power and efficiency.

### DURABILITY SURVEILLANCE: MITIGATING THE RISK OF NEW TECHNOLOGIES

For all their cost, performance, and siting advantages, the newer gas turbines are perceived as a risky investment by financial institutions [3]. New F-class, as well as older E-class machines have failed more often than anticipated—more than 5% of them catastrophically [4]. To mitigate the risk of investing in new offerings, EPRI conducts a rigorous durability surveillance program, working with host utilities and OEMs to monitor at least one early installation of each major new introduction, beginning with the F-Class. The surveillance program tracks each plant for three to five years, addressing power, heat rate, availability, and maintenance. Table 1 summarizes both the peaking and baseload installations that EPRI has investigated. In addition, we are planning to monitor smaller turbines, including the Allison ATS machine at Indiana Power and Light, and are beginning surveillance of 25-kW microturbines at Northern States Power and Southern California Edison.

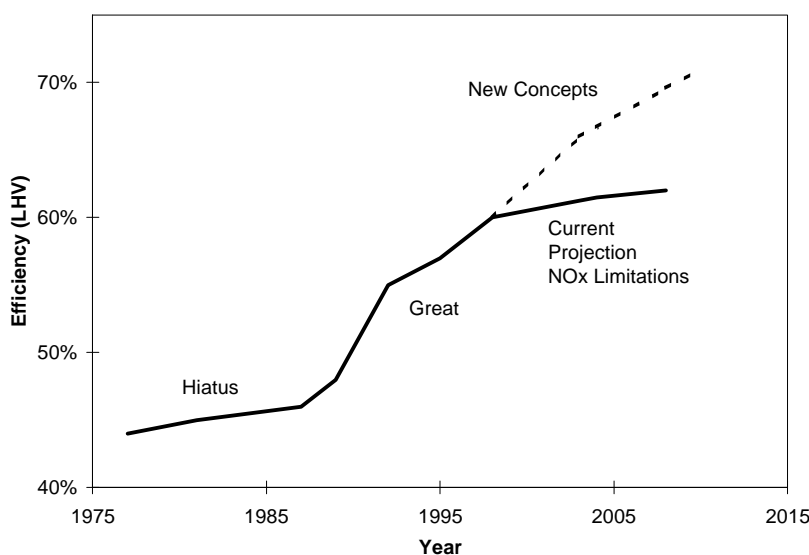
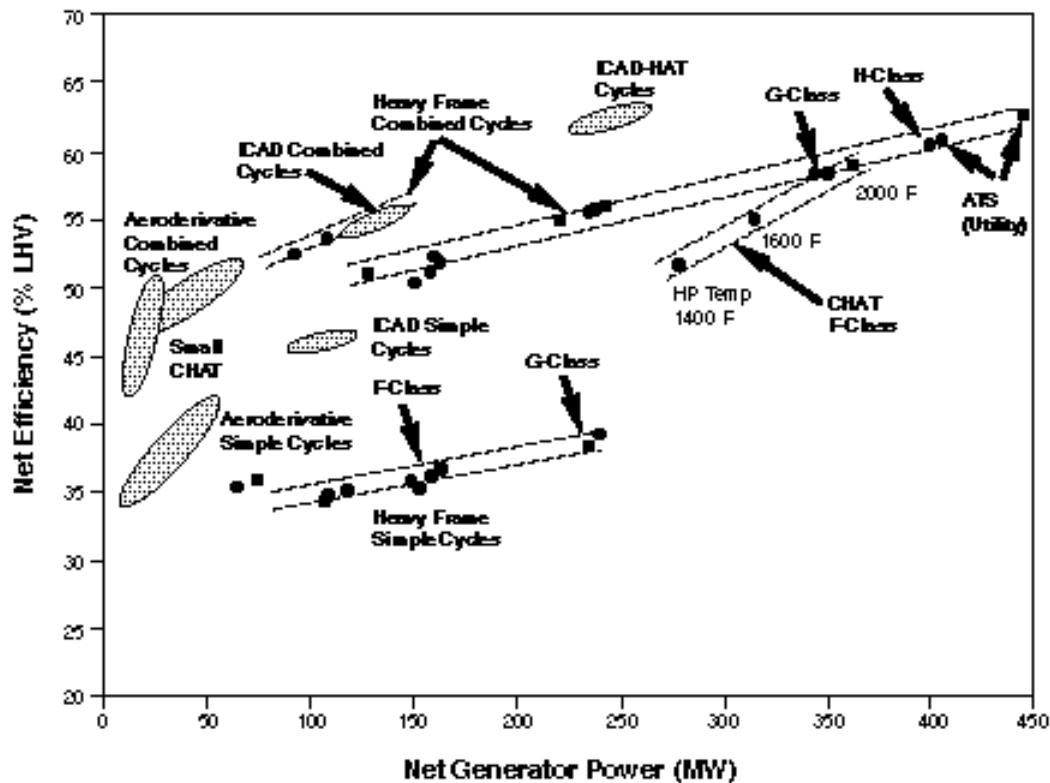


Figure 1. Efficiency Improvements in Combined Cycles



## 2. Current and Projected Technologies

using optical pyrometers and EPRI-developed analysis software. Dynamic sensors monitor a full slate of locations proximity data. Because new low- $\text{NO}_x$  combustion systems are particularly susceptible to pressure pulsations (buzzing and humming), pressure-induced

3 shows the specific instrumentation locations on the ABB

Monitoring and Analysis Program (E-Map) developed by EPRI and ENTER Software, investigators will also track

Low-tech monitoring devices can also be very useful. For example, video and chipping of 2–3 disk spacer at Potomac Electric Power's Station H. Although relatively minor in itself,

flexibility. GE has subsequently instituted remedial measures, including redesigning the 2–3 wheel spacer. By

appropriate operational limits with minimal disruption to utility customers [ ,6

Inspections have also been important. For instance, examinations at pyrometer measurements indicating that first-stage blades were, on average, too hot. Though researchers initially operational data, visual examination revealed excessive oxidation, which was traced to overheating of first-stage misaligned rotor restricting cooling air flow.

could have detected most problems on machines monitored by EPRI and at other installations. Therefore, EPRI

(particularly F-, G-, H-, or ATS-class machines)

regime, and back it up with a rigorous inspection program. EPRI has summarized initial findings from its durability 7], and will incorporate

guidelines for EPRI members.

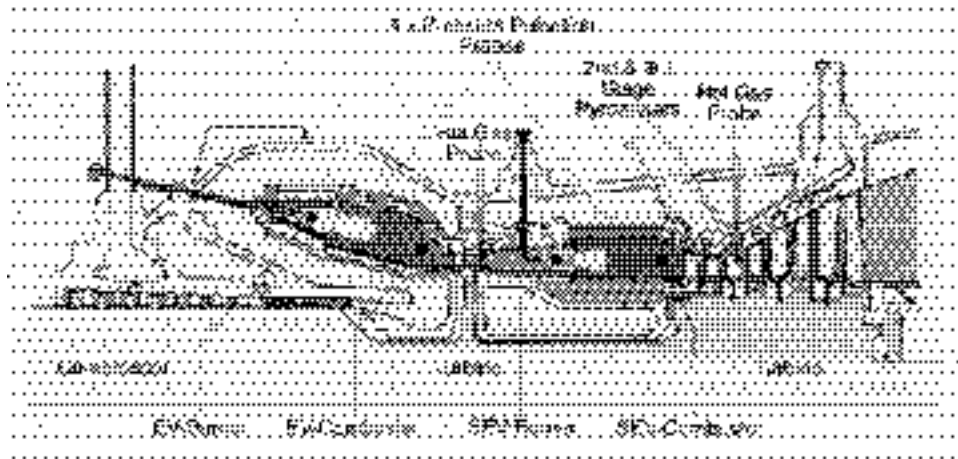


Figure 3. Specific locations of monitoring instruments on the GT24 at Jersey Power and Light

Table 1. F-Class combustion turbines monitored through EPRI's durability surveillance program

GE 7F	Potomac Electric Power's Station H	peaking (simple cycle)	gas/distillate oil
GE 7FA	Florida Power and Light's Martin Station (4 turbines)	baseload	natural gas
GE 7FA	Cinergy's Wabash River Plant	baseload	medium-Btu coal gas
ABB GT24	GPU GENCO's Gilbert Station	baseload	natural gas
Siemens V84.3A	Kansas City Power and Light's Hawthorn Station	peaking	natural gas

## IMPROVING TURBINES AND CYCLES

In addition to evaluating new commercial offerings, EPRI is developing cycles that offer higher efficiency, faster starts, and lower capital costs. We were involved at the inception of closed-circuit steam cooling research, demonstrating that this technology could boost cycle efficiency by two points (4%) [8]. We have also investigated cycle enhancements such as sequential combustion, intercooling, humidification, and recuperation, incorporating them in our own cycle designs and programs, notably the CHAT and intercooled aeroderivative (ICAD).

### Cascaded Humidified Air Turbine (CHAT)

Cascaded Humidified Air Turbine (CHAT)\* technology grew out of earlier EPRI work on compressed air energy storage and humidification. As shown in Figure 4, CHAT integrates compressor intercooling, recuperation, and reheat into a humidification cycle, producing a cycle that integrates combined-cycle efficiency with simple-cycle start-up times. In the CHAT cycle,

compression work is divided between the LP compressor on the power generation shaft and the IP and HP compressors on a separate, power-balanced shaft driven entirely by the HP turbine.

The addition of IP and HP compressors significantly reduce the LP compressor load by shifting the bulk of compression work to the HP shaft, resulting in a shorter time to synchronization. Startup is further shortened by the absence of steam bottoming, making this technology ideal for cycling service.

CHAT plants also maintain high efficiency at part-load, while the maximum power output remains virtually independent of ambient conditions. Higher levels of water evaporation compensate for reduced air flow at high ambient temperatures or low pressures, and the resulting increase in mass helps maintain power output. Additionally, the HP shaft is uncoupled from the power shaft and does not have to be synchronized to the grid. This means that the HP shaft is free to operate at optimum speeds on hot days or at high elevations.

The first-generation CHAT design combines a Westinghouse W501F on the power generation shaft with Dresser-Rand turbomachinery on the HP shaft with HP and LP firing temperatures at 1600F and 2370F respectively. This yields a full-load output of 316 MW at 54.7% efficiency. Using commercially available technology is key

\*CHAT technology was developed in cooperation among EPRI, ESPC, and CAT-LP. The patent rights covering the CAT/CHAT technology are jointly owned by EPRI and CAT-LP.

reliability of CHAT design.

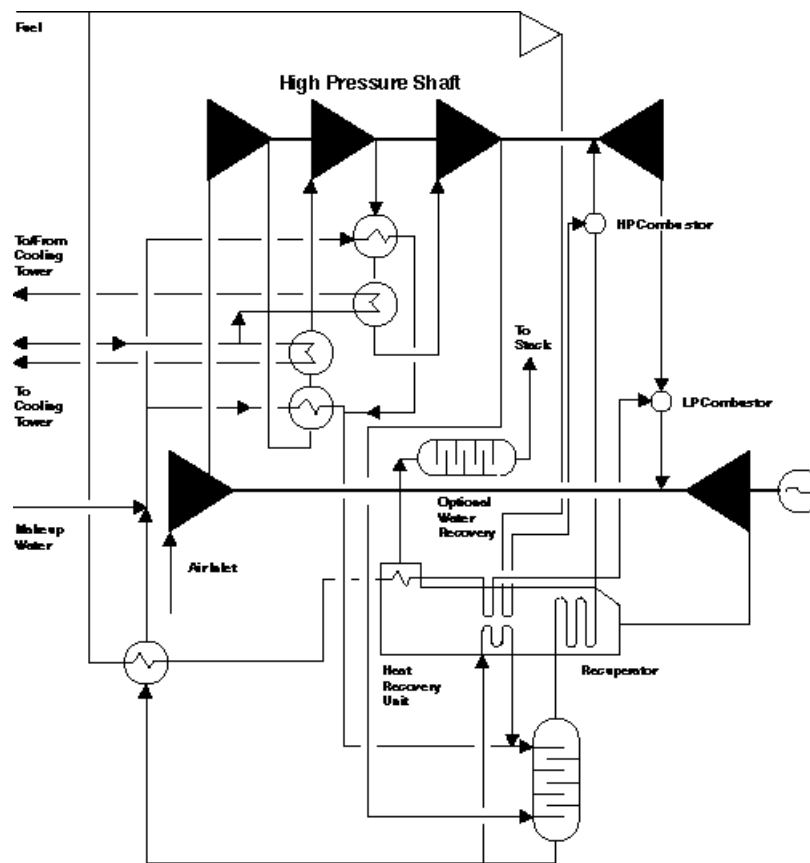


Figure 4. The CHAT Design Incorporates Compressor Intercooling, Recuperation, and Reheat into a Humidification Cycle

### Small CHAT

The CHAT cycle is also being applied to plants in the 10–25 MW range. EPRI has developed a design that uses an unmodified Allison 501 compressor/turbine on the LP shaft in combination with Dresser-Rand machinery on the HP shaft. However, due to the unmodified Allison compressor, this design experiences higher pressure and temperature downstream of the compressor than previous CHAT designs. This issue is addressed by the addition of recuperation and hot water heating, and power generation on the HP shaft. The result is an 11–12 MW power plant with an impressive 44% efficiency. 9

The small CHAT, as with the 300 MW design, offers rapid startup and maintains high efficiency at part-load. Additionally, it also yields significantly higher full-load efficiency at lower capital cost compared to a combined-cycle plant of the same output. This is due mainly to the high specific cost and low efficiency of small steam turbines.

### Next Generation CHAT Plant

CHAT designs using F-class turbine components can obtain the same efficiency as the latest combined cycles that use the most advanced technology. EPRI has also studied CHAT performance for HP turbine inlet temperatures between 1600–2100F (870–1150C). At 2100F, efficiency is predicted to be 58–60%, and power is increased to 354 MW. The designs for both 3- and 4-stage turbines appear practical—offering high stage efficiency and limited cooling losses. These predicted efficiencies match those of the latest combined cycles, yet the turbine firing temperatures are moderate compared to the 2600F (1430C) firing temperature level of the “G” and “H” class turbines.

The increase in power indicates that this design should reduce specific capital cost by about 10%, even with the increased cost of the cooled high pressure turbine. Thus, at 90F (32C) ambient temperature, the CHAT plant could enjoy about a 20% advantage in capital cost compared to combined cycles. With the HP turbine providing the power required to drive all of the compressors, startup times for the new CHAT will drop even further. EPRI is

planning to issue an RFP to turbine developers for the

### Water Recovery from Humidified Power Cycles

As the issue of water use becomes ever more critical in advantage over humidified cycles by making use of once-through ocean or river cooling or dry cooling towers. For feasible and economical method for water recovery is necessary. EPRI has investigated the use of in-stack desaturator followed by water clean-up and reuse. Of the two options, the latter was found to be cost and heat rate penalties.[11]

Figure 5 illustrates a scrubber desaturator system. condensed in a direct contact cooler, where a large volume of cold water flows down through packing material and desaturator along with the cooling water and gets split into two streams, one returning to the cycle and the other desaturator after being cooled.

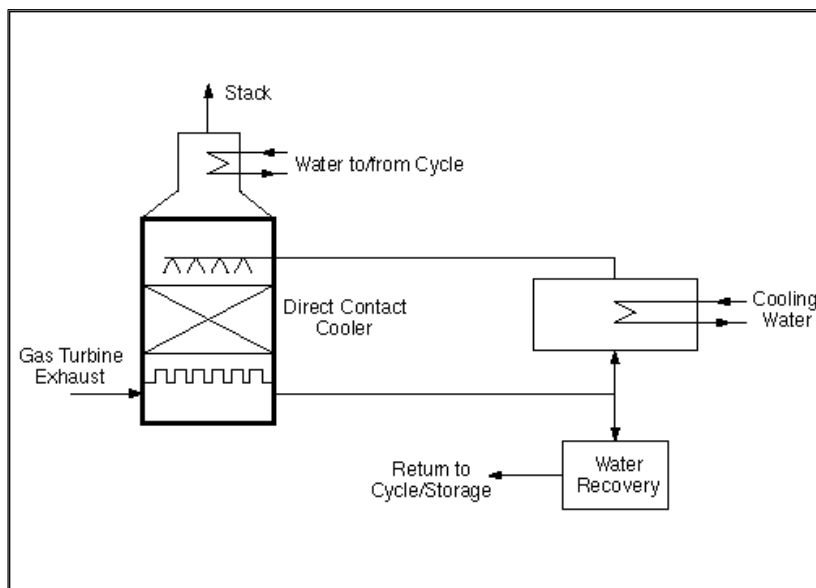
The EPRI study focused on a 300 analyzing the size and cost of water recovery and clean-up equipment as well as performance degradation due to conditions. Compared to a CHAT cycle with no stack or blow-down water recovery, the capital cost rose only Btu/kWh for once-through cooling, while the capital cost increased by cooling tower. However, when compared to an F-class combined-cycle plant with water recovery, the CHAT still

23 Btu/kWh for once-through cooling, and \$48/kW and Btu/kWh for a dry-cooling tower.

### Intercooled

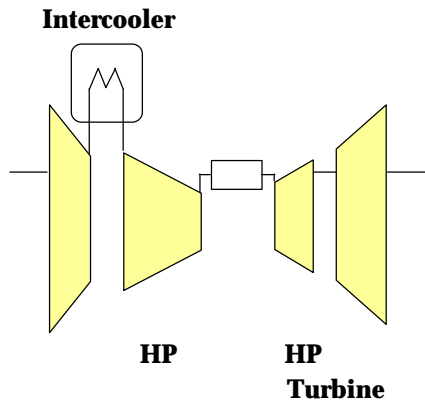
Aeroderivatives are ideal for peaking and load-following service since they deliver quick starts and LM6000C and Rolls Royce Trent have simple-cycle efficiencies of 41–42%, which can be boosted to 45–50% reducing compressor work and increasing pressure ratios and mass flow, intercooling provides cooler air to the increases efficiency.

EPRI is pursuing ICAD turbines (Figure with the Collaborative Advanced Gas Turbine group (CAGT), an international consortium of electric and gas organizations, and DOE's ATS program. The consortium from 20 MW–120 MW design boasts a simple-cycle efficiency of 46% with a capital cost similar electricity at a lower cost than simple- or combined-cycle CTs that operate from 10–40% of annual hours. Other than five minutes); exhaust temperatures suitable for cogeneration; and salvage values as high as 50%. feedwater pre-heating, and repowering, ICAD can be sited



**Figure 5. Water Recovery System for Humidified Cycles**

in dispersed or central station locations. In markets where large blocks of power are needed, multiple 100+ MW simple-cycle ICAD units can compete with G- and H-class combined-cycle plants. Although ICAD unit efficiency is lower, its dispatch efficiency could be higher because individual machines are turned off to achieve part load. Further, the multiple ICAD configuration offers reliability through redundancy.



**Figure 6. The intercooled aeroderivative builds on the high performance of jet engines, resulting in a flexible, compact power plant with a simple-cycle efficiency of 45–50%.**

## **FUTURE DIRECTIONS: COMBINING TECHNOLOGIES**

In order to boost efficiencies beyond 60%, EPRI is modeling designs that combine recent advances [12]. For

example, sequential combustion and closed-circuit steam cooling are attractive candidates for combination. Applying ATS or H-class steam cooling technology to the LP expander of an ABB GT24 would raise the firing temperature to 2600F, leading to a projected efficiency of 61.4% with a substantial rise in specific power. However, in this case, the overall pressure ratio would also jump to 64:1, exceeding the current capabilities of a single-spool compressor. This difficulty can be overcome by adding a low-pressure-ratio (2.2:1) boost compressor with an intercooler before the main compressor. Thus, by using all off-the-shelf hardware, efficiency can be raised more than three points higher than the current ABB GT24 and about one point higher than a single-turbine H-class configuration—with no increase in NO<sub>x</sub> emissions.

Extending steam cooling to the HP turbine and operating at 2700F would raise efficiencies up to 65% (Figure 7). Moreover, specific power would also rise by more than 50%—an important factor in reducing capital costs. These additional gains would require higher-pressure casings and combustors, which exceed current gas turbine practices. However, commercial high pressure steam turbine technology has been adapted for lower-temperature (approximately 1500F) gas turbines, and could probably be adapted for higher-temperature (2300+F) gas turbines as well. Finally, G- and H-class technology could be combined with the CHAT cycle to yield cycle efficiencies approaching 65%.

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**Figure 7. Projected Efficiencies for Combined Technologies**

## CONCLUSION

EPRI gives its members a view of future strategic options for planning and procurement by collaborating with users, DOE, GRI, manufacturers, and others to help determine market needs and technology options. Through its durability surveillance program, EPRI works to reduce risk and increase reliability associated with applying new machines. The Institute continues to support advances in cycle efficiency and flexibility by developing efficient cycles with rapid start-up rates and high part load efficiencies. The end goal of these efforts is to increase the competitiveness of its members.

## ACKNOWLEDGMENTS

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